→ ATLANTIC FROM SPACE WORKSHOP

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Regional sea level, sea state change in the Atlantic from space

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Content

Within the Atlantic context, we address contribution and limitation of remote sensing to the issues:

1) Sea level and sea state in coastal zone
2) Regional sea level budget
3) Ocean circulation

IWW:

1) Implication of Thema
2) What is done
3) What can be done

Sea level and sea state in coastal zone

1) Implication : Climate Change, Coastal protection

2) Done: Coastal sea level by altimetry and tide gauges, VLM

3) What is still needed

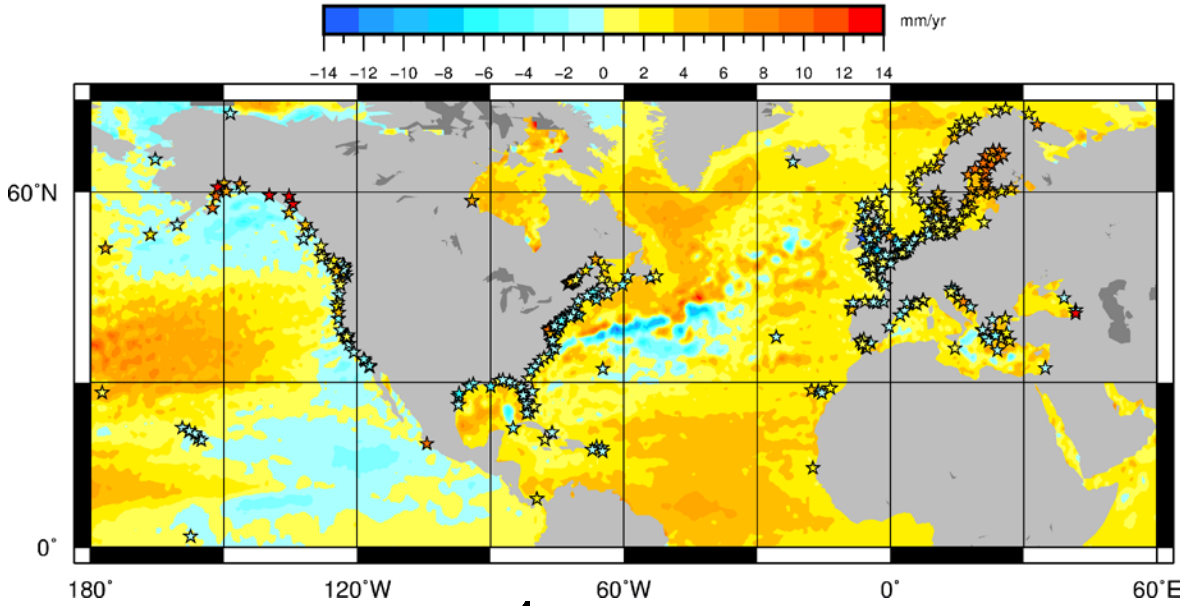
Coastal sea level (SL)

Climate change → Absolute SL trends from altimetry (background) & relative SL TGs

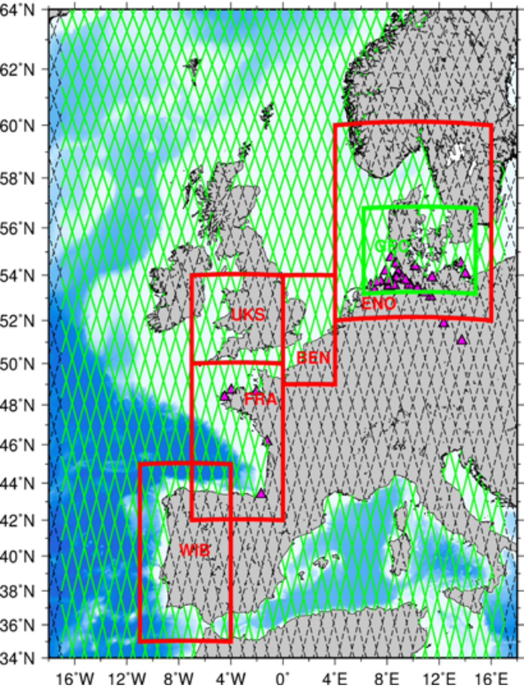
altimetry minus tide gauge trends (VLM, stars) smaller than 1 mm/yr in mean and RMS differences of few centimetres.

Hotspots of accelerated sea level rise on the Atlantic coast of North America (Sallenger et al. 2012)

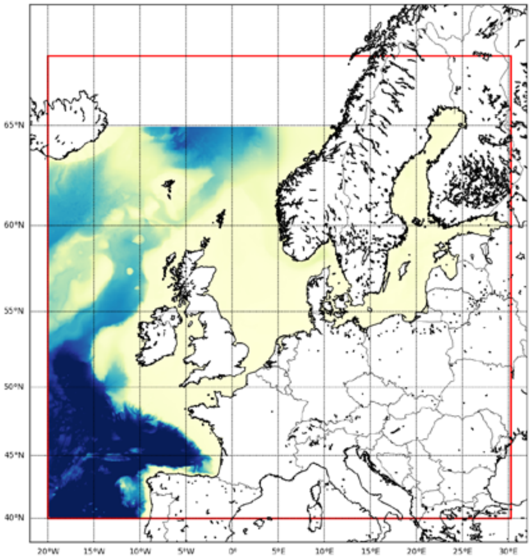
On the eastern Atlantic (European coast) 2-3 mm/yr

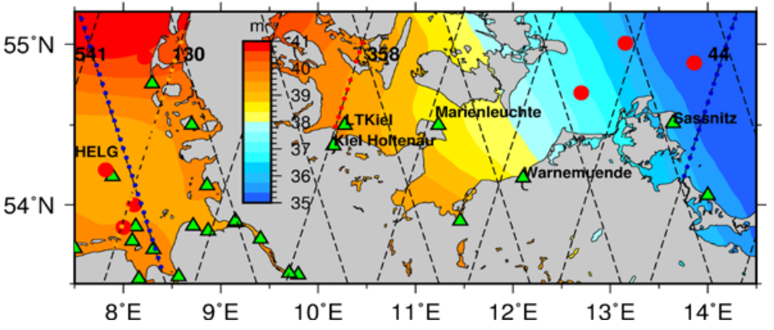


Coastal sea level (SL)



Sentinel-3A ground-tracks

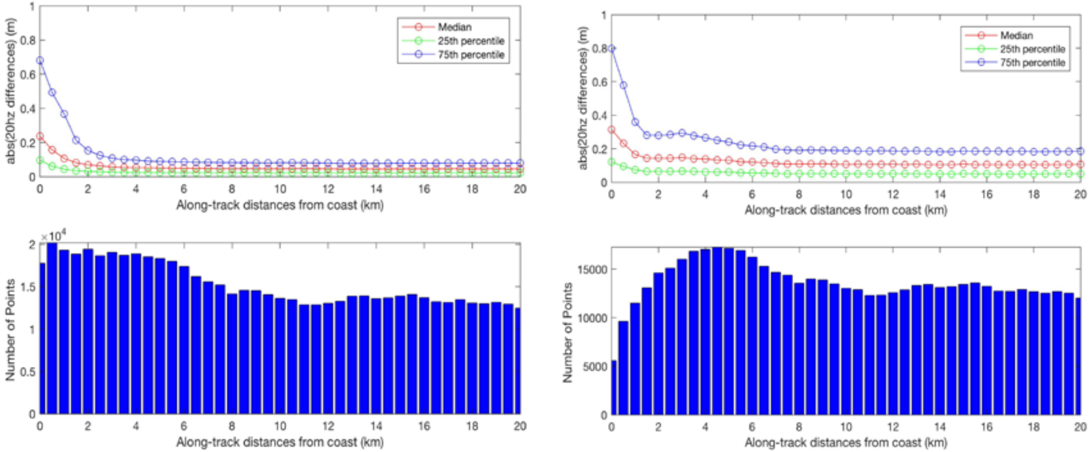


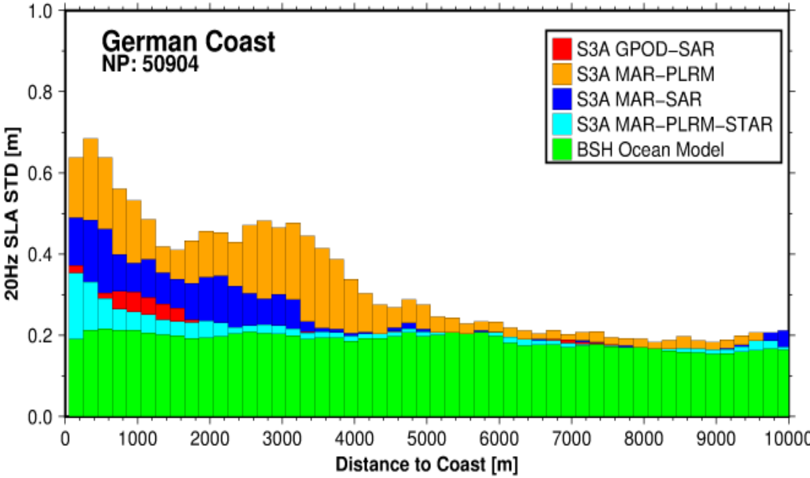


Challenge: analyse coast with networks in-situ stations for CAL/VAL (e.g. Western Europe and US)

GCOAST Geesthacht Coastal Model System that integrates different models and scales
Integrating waves, circulation, atmosphere and HD model

Coastal sea level





Sentinel-3 altimetry SAR (l) and PLRM (r) in 2016-2017.

Noise (above) and NPoints (below) against along-track distance from coast. Noise is the absolute value difference between consecutive sea level heights (SSH) measurements.

Standard deviation of S3A SLA for two SAR and two RDSAR products

(Fenoglio et al., 2018)

Coastal sea level

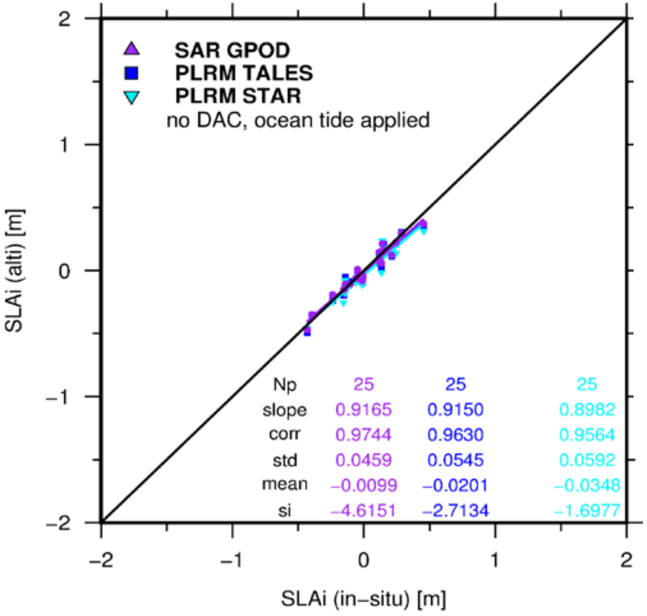
(Dinardo et al. 2017) **Altimetry** better agreement then model to in-situ

COASTAL ZONE	PLRM TALES			PLRM SINC2			SAR			BSH			
Index	stdd cm	slope	Corr	stdd cm	slope	Corr	stdd cm	slope	Corr	stdd cm	slope	Corr	Number of Points
HELG	4.23	0.96	0.96	11.7	0.93	0.86	3.3	1.00	0.97	18	85	0.75	67
KOSE	11.5	1.240	0.96	37.6	1.16	0.86	2.4	1.02	0.97	7.10	0.84	0.75	35
LHAW	9.1	1.01	0.96	16.7	1.00	0.86	7.8	0.99	0.97	21.2	0.75	0.75	58
SASS	6.5	1.03	0.89	13.6	0.86	0.78	4.3	0.99	0.95	6.10	0.98	0.85	28
WARN	11.1	1.047	0.87	21.8	1.076	0.74	4.3	1.02	0.97	9.60	0.87	0.87	22

Table 1: Statistics of the SLAio in situ cross-comparison for SAR, PLRM TALES, PLRM SINC2 and BSH Model dataset in the coastal zone (0-10 km). The distance from the station is between 0 and 10 kilometres.

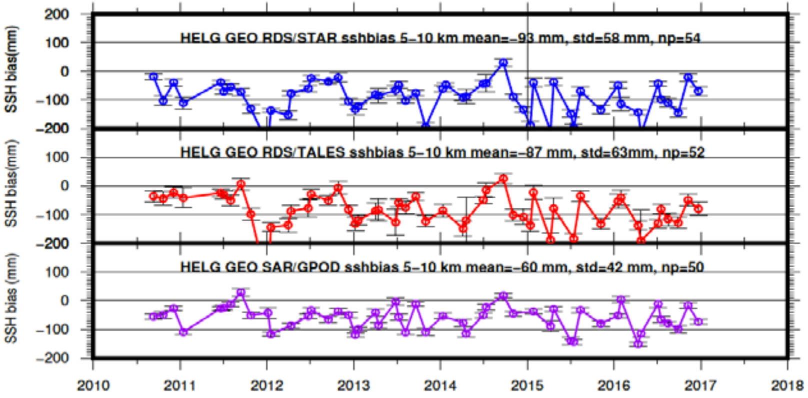
(Dinardo et al., 2017)

Coastal sea level



CryoSat-2 altimetry and in-situ SLA (in 2016-2017) at 10-20 km from station Helgoland

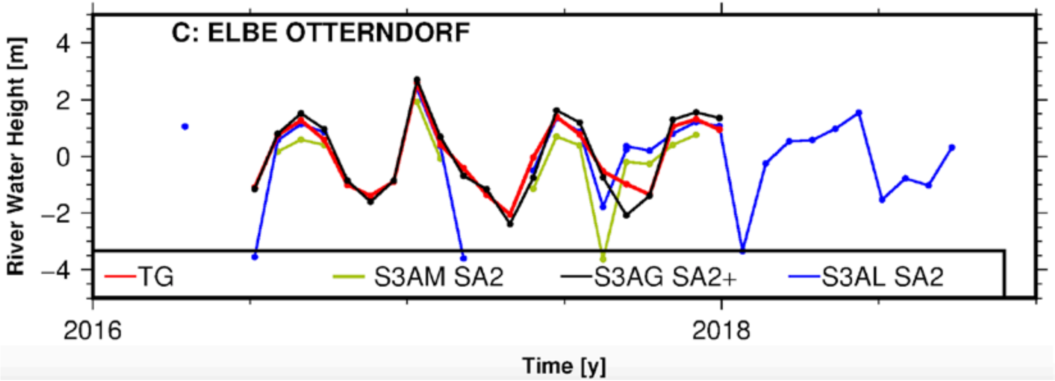
(Fenoglio et al., 2018)



CS-2 bias 5-10 km from HELG (above)

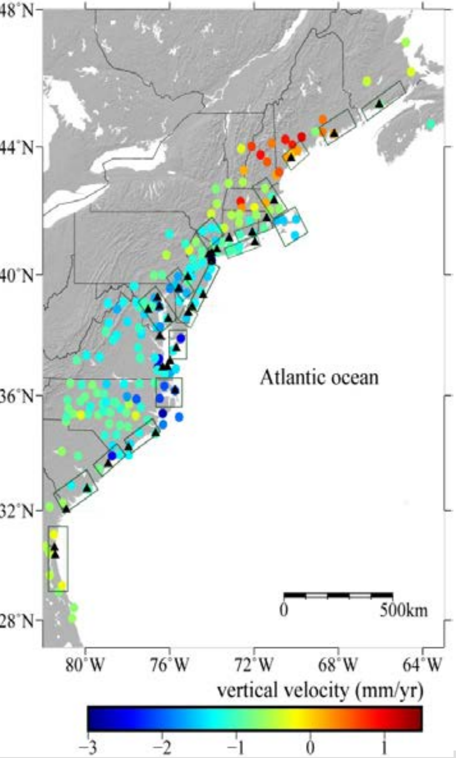
and
S3A & in-situ SLA with

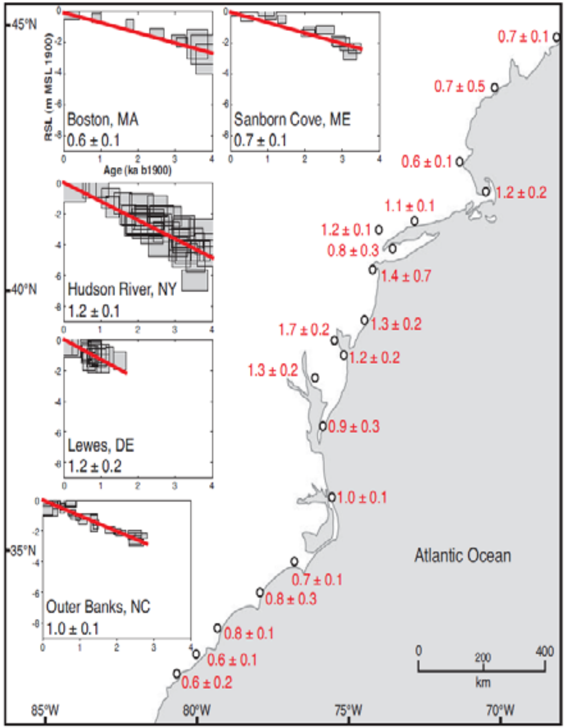
RMS 20 cm (below)

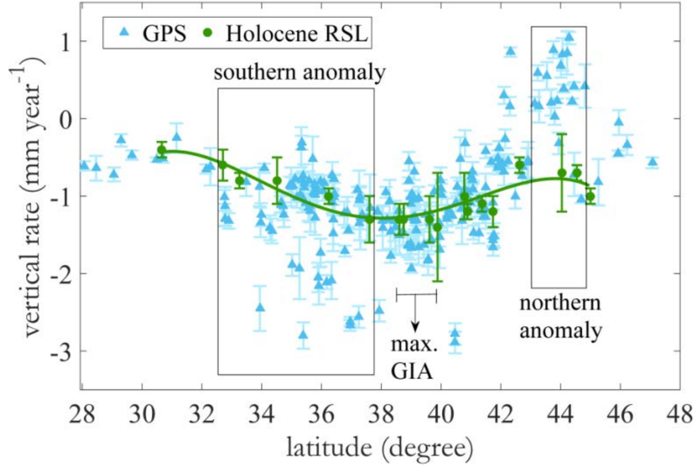


Vertical land motion along the Atlantic Coast of North America

GPS Karegar et al. (2016) Holocene RSL







subsidence of eastern seaboard of NA continues with constant rate with GIA as the main deriver. Exceptions are related to areas of recent excessive groundwater extraction and dam retention.

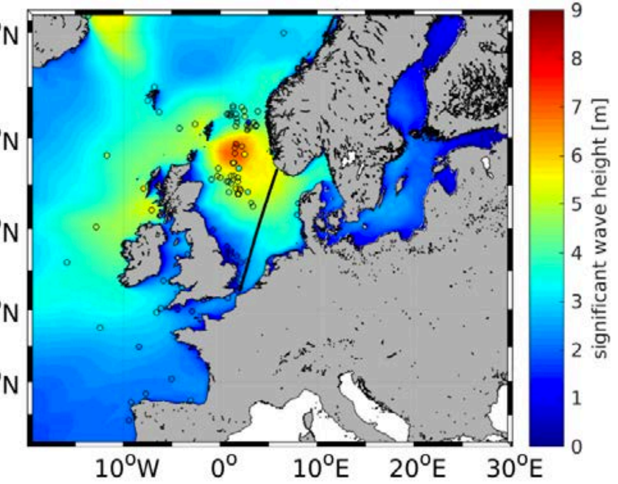
(Dinardo et al. 2017) **Model** better agreement than altimetry with in-situ

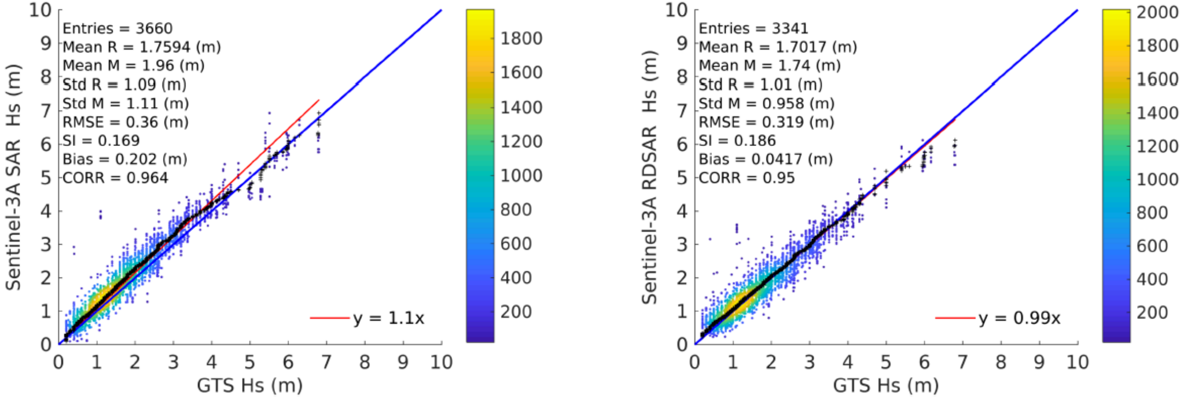
Measurement	DWD SWH				PLRM SWH				SAR SWH				
Index	mean cm	stdd cm	Corr	slope	mean cm	stdd cm	Corr	slope	mean cm	stdd cm	Corr	slope	Number of Points
HELG SUD DWR	-13.6	24.8	0.96	0.98	-14.7	62.6	0.73	0.6	3.4	38.7	0.91	1.13	32
HELG NORD DWR	-8.7	25.7	0.95	1.05	-23.6	49.7	0.78	0.92	7.1	39.1	0.87	0.94	39
WES DWR	18.4	19.1	0.89	0.85	-15.3	27.5	0.98	1.27	-1.5	15.7	0.95	0.93	15

Table 3: Statistics of the SWH in situ cross-comparison for SAR, PLRM TALES, DWD datasets in the coastal zone (0-10 km). The distance from the station is between 0 and 10 kilometres.

Coastal Sea state

Wiese et al. 2018





(a) (b)

SAR Altimetry better agreement then previous satellites

S3A, J2 and C2 SWH assessed against in situ & and spectral wave model (WAM) simulations forced with meteorological data to evaluate the sensitivity to wind different spatial/temporal resolutions

SWH from satellite > in situ by 7 cm to 26 cm. Near coast satellite data quality decreases; but within 10 km off the coast, Sentinel-3A performs better than the other satellites

(Fenoglio et al., 2015)

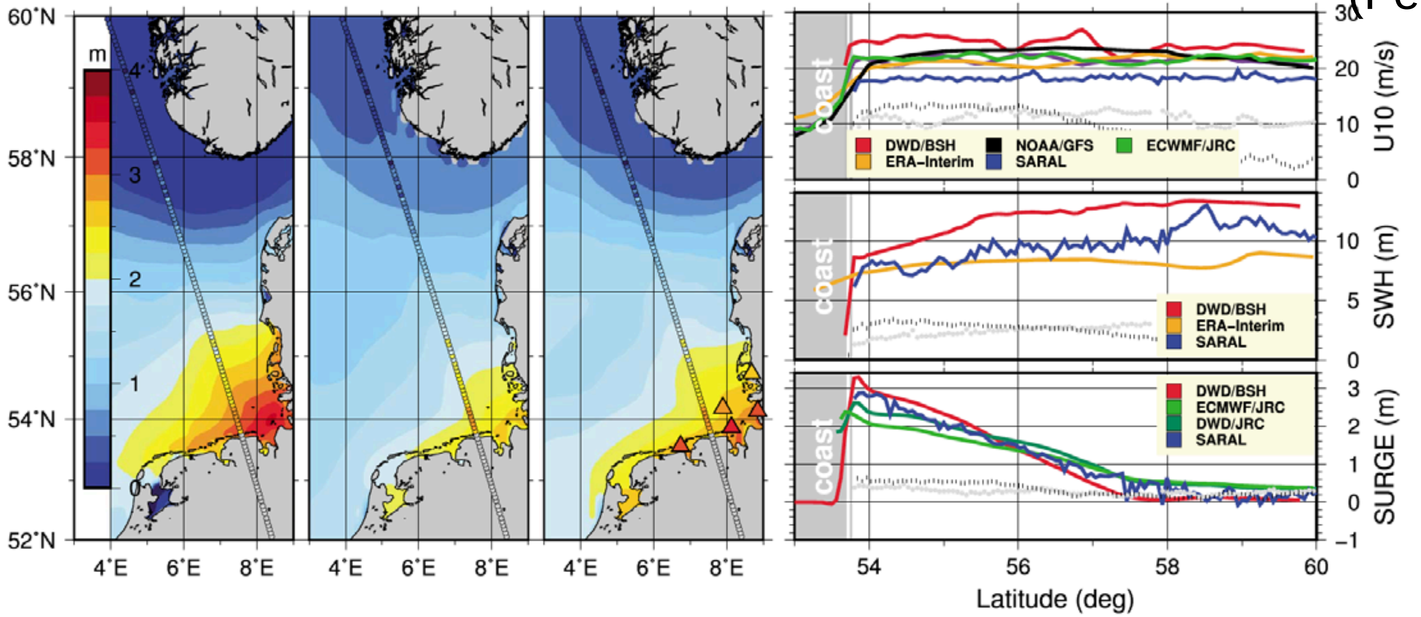


Figure 3. (left) Surge at the time of the overflight predicted by BSHcmod and HyFlux2 simulations with various wind forcing (DWD/BSH, ECMWF/JRC and DWD/JRC from left to right) and derived from in situ data (triangle). (right) Profiles at the SARAL/AltiKa overflight of wind speed, significant wave height, and surge height derived from altimeter observations (blue) and from models (red for DWD/BSH, light green for ECMWF/JRC, dark green for DWD/JRC, orange for ERA-INTERIM, and black for NOAA/GFS). Gray lines correspond to observations before (continuous line) and after Cyclone Xaver (black points).

Sea level and sea state in coastal zone

1) Implication : Climate Change, Coastal protection

2) Done: Coastal sea level by altimetry and tide gauges, VLM

3) What remains to do:

Reduce coastal gap < 2-3 Km

improve SLA accuracy and precision (error estimation)

continuity coastal/estuaries/in-land waters

- Enhanced Conventional
- Delay Doppler (DDA) altimetry/SAR
- fully focused SAR
- “swath-altimetry” (SWOT mission)
- Synthetic Aperture Radar imaging

Sea level and sea state in coastal zone

1) What remains to do (cont.):

For coastal altimetry we have to

separate SLA sea surface variability and altimeter noise-> we need **better models** of the temporal correlation of sea surface variability (wrt new technologies with improved temporal sampling GNSS-IR, SWOT) and **new methods** to account for this (10d SSH physically decorrelated, SWOT 1-2d not).

For VLM we have to

connect GNSS VLM with altimetry

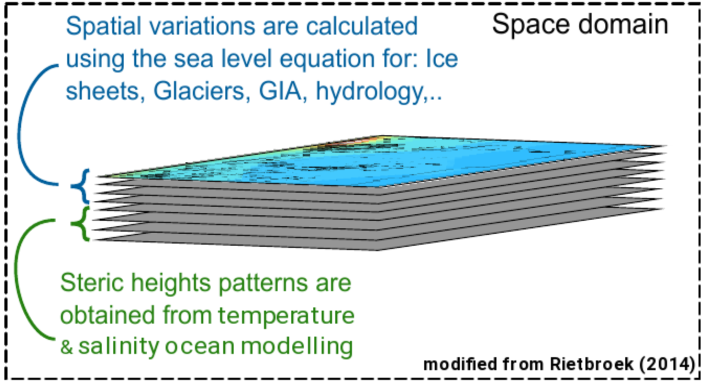
separate local and episodic/nonlinear VLM from VLM along entire coastlines and trends
☐ we need better **models/data/methods** (SAR, sea state, coastal tide models)

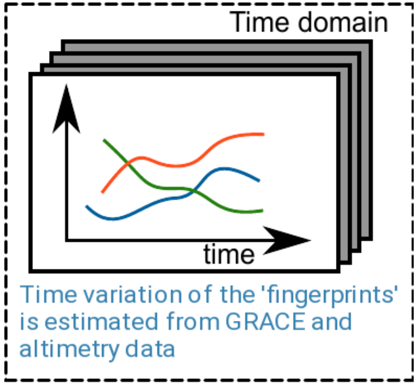
1) Implication : Climate Change & Coastal protection

2) Done: direct comparison of GRACE & altimetry & model simulations

3) What is still needed

- Idea of the global fingerprint inversion (Rietbroek et al., 2016)
  - Forward modeling of gravitationally-elastic rotationally consistent sea level patterns → **fingerprints**
  - Consistent treatment of reference frames
  - Time-variable amplitudes are fitted to time-invariant fingerprints





Budget: Combination of GRACE and radar altimetry

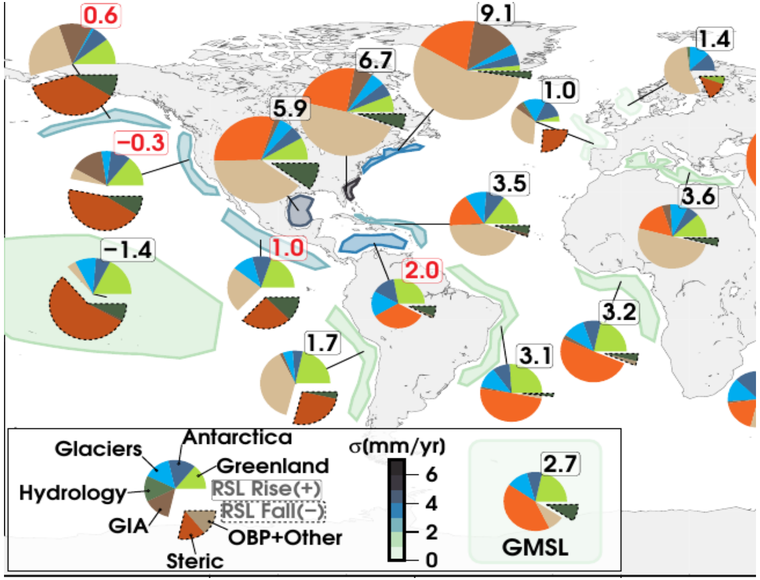
UBonn / IGG / APMG approach: Global inversion

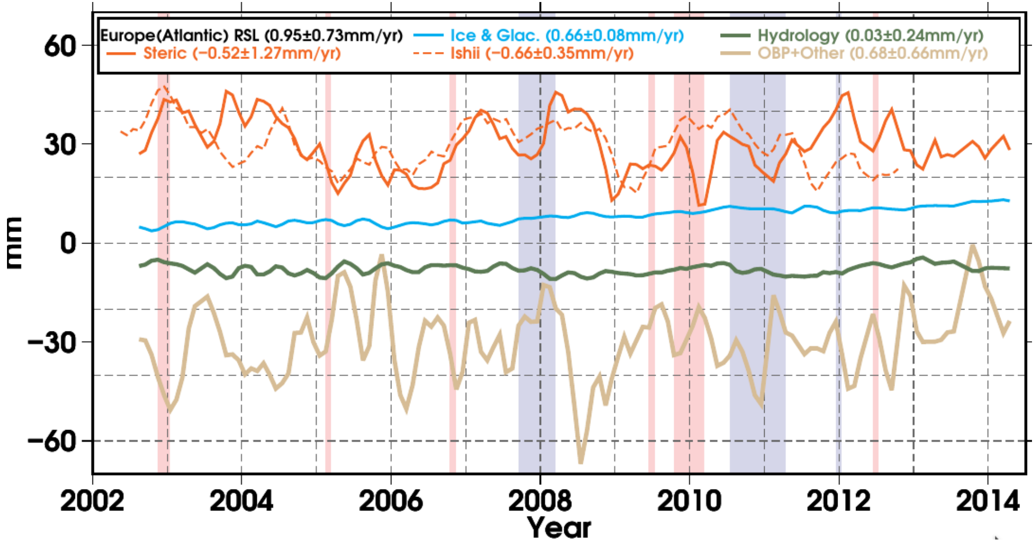
GRACE (mass driven sea level) versus radar altimetry (total geocentric sea level)

→ combine and resolve for sea level budget components,

0.95 + 0.36 = 1.31 mm/yr

1.74 from AVISO





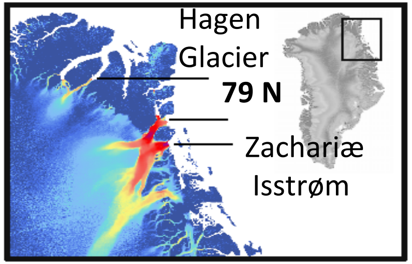
Rietbroek et al. 2016

UBonn / IGG / APMG approach: Global inversion + Ocean Modelling

Aim:

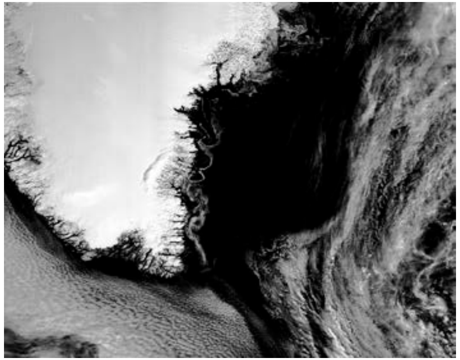
- Resolve consistently for mass changes over land and steric changes in the ocean
- Improve understanding of changing dynamics of Greenland icesheet (Greenland ice sheet Ocean Interaction, GROCE)
- Feedbacks of Greenland glacier melting in the NA and Arctic

Focus: 79N glacier & North East Greenland Ice Stream (NEGIS).



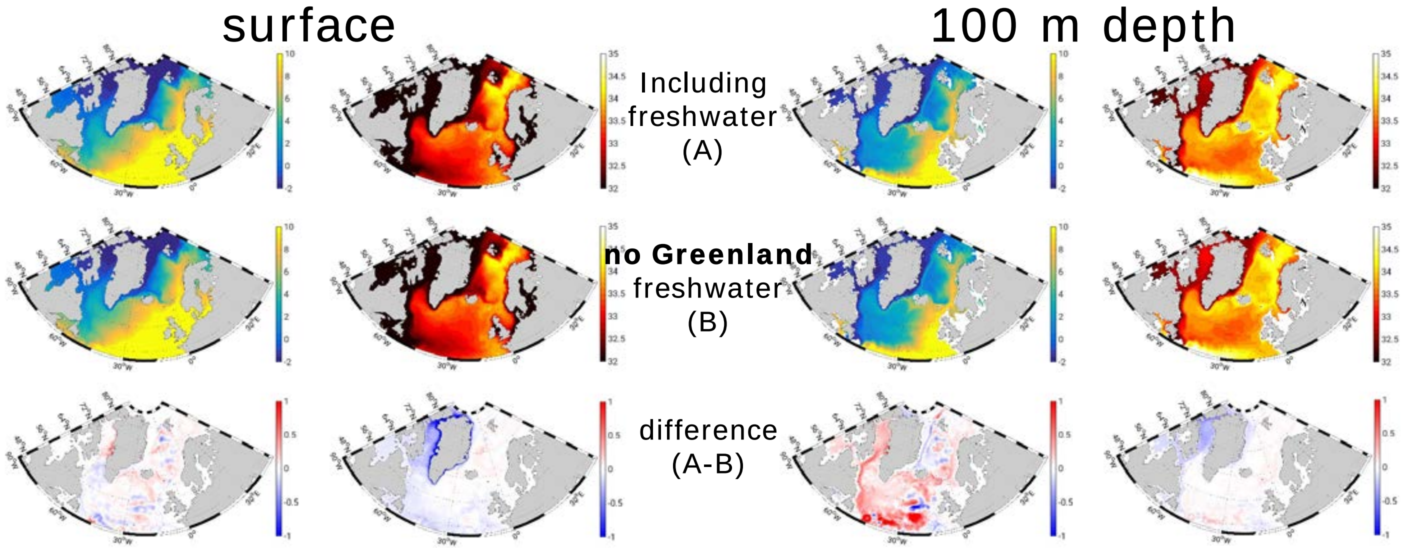
Analyzes

- mass balances of Greenland (GRACE gravimetric data)
- sea level budgets of NA (radar altimeter data)



We study relevant changes in temperature and salinity by oceanographic modelling

- global ocean model FESOM (AWI); forced with JRA-55; temperature [°C] and salinity [psu]



Further plans: Compare with GRACE and SWARM data and satellite altimetry

– Increase model resolution in the Arctic and around the 79N glacier

Regional sea level budget

1) Implications: Climate Change & Coastal protection

2) Done: direct comparison of GRACE & altimetry & model simulations

3) What is still needed :
   - Improved data (sea ice altimetry and GRACE, climatic data)
   - assimilation in model simulations

Dynamic Topography

1) Implications: Climate Change & Coastal protection & Vertical Datum Unification & Navigation

2) Done: various methodologies tested (ocean & geodetic approach) for low resolution surface, here time variable approach

3) What is still needed :

Estimation of the MDT

observations

Gravity field model

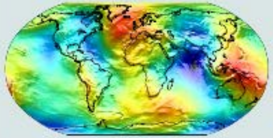
- purely GOCE based
- time-wise model
- band-limited

Altimetry

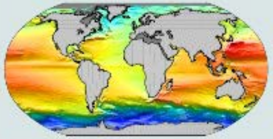
- along-track SSH
- Jason1 cycles
- Envisat cycles
- high resolution

parameterization

separation



Geoid
- global spherical harmonics
- high resolution



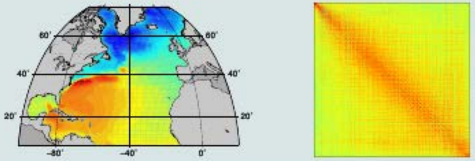
MDT
- finite element base functions
- local area

combination

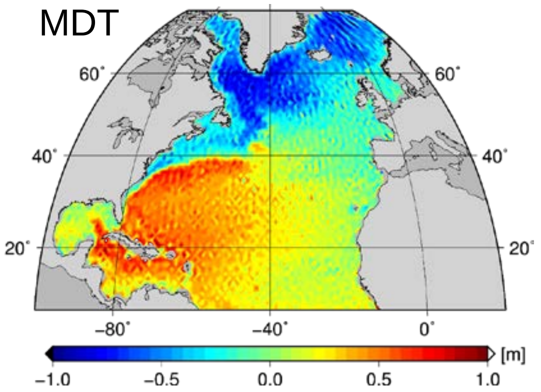
joint adjustment

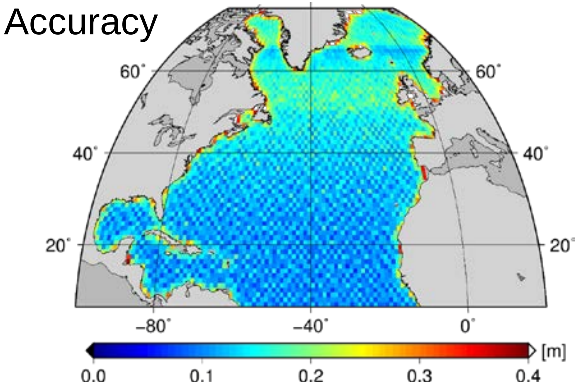
spherical harmonics:
- nuisance parameters
- buffer for high frequency altimetry
- eliminated from NEQs

MDT on predefined grid + VCM



finite elements:
- target quantity
- currently: local focus
- resolution defined by grid and base functions





Becker etal. (2014a,b)

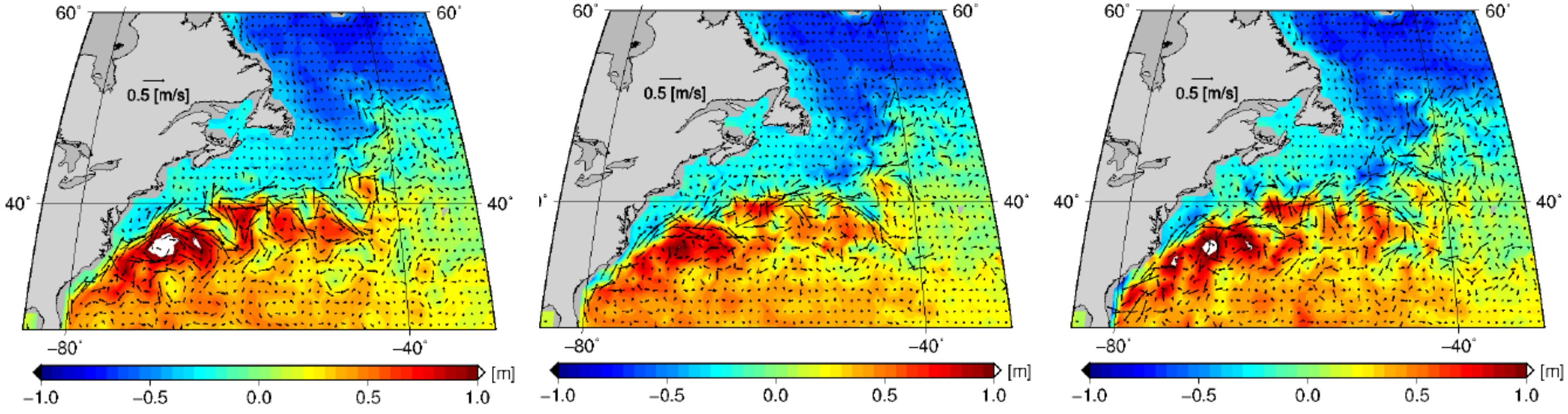
Estimation of the DT

Time variabilty can be modelled make the FE coeffcients continuous functions in time

$$\zeta(\theta,\lambda,t) = \sum_{k\in K} a_k(t) b_k(\theta,\lambda) = \sum_{k\in K} \left[\sum_{i\in I} a_{ki} B_{ki}(t) \right] b_k(\theta,\lambda)$$

(Müller, 2014, Müller etal. 2015)

Example result: Dynamic Topography for 5/2005, linear finite elements in space, B-Splines in time



Reference: AVISO

from: GOCE + Altimetry

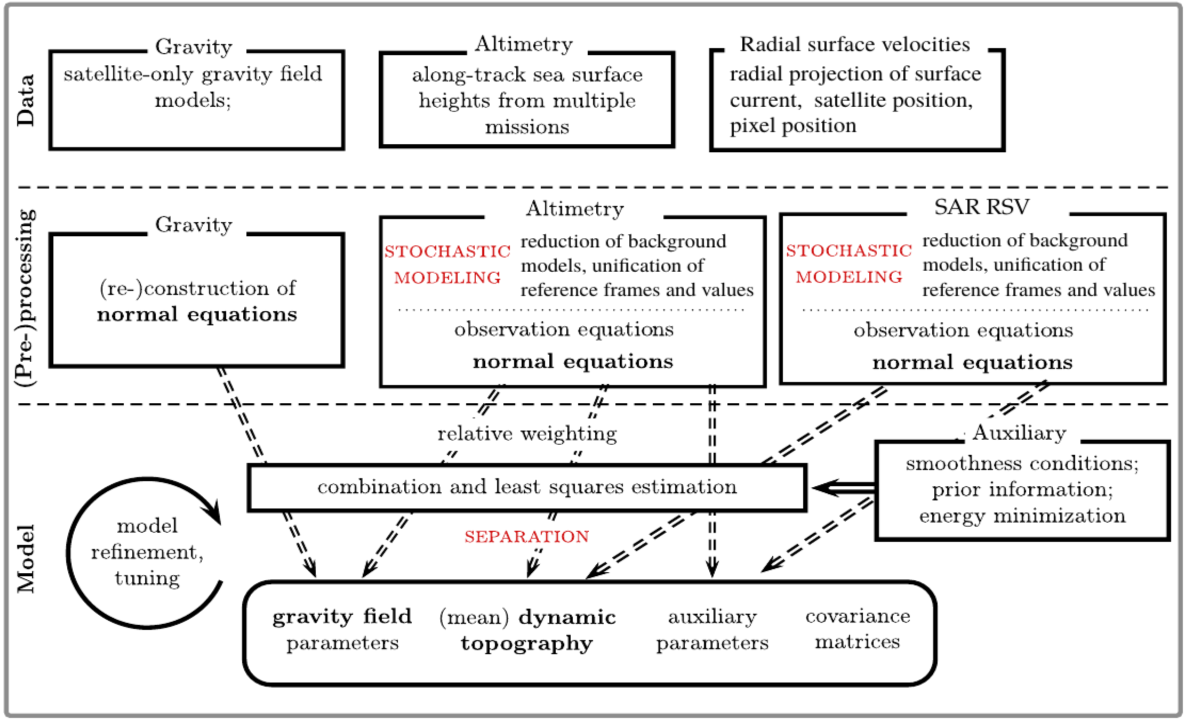
from: GOCE + Altimetry + ARGO + SVP

DT from project PARASURV (DFG)

PArametric determination of the dynamic ocean topography from geoid, altimetric sea surface heights and SAR derived **RA**dial **SUR**face Velocities

Goals:

- Develop and implement a C^1-smooth FE space to model MDT
- Observation equations link (reduced) current observations to MDT (radial SAR doppler derived, SKIM, …)
- Implementation in HPC environment for real data analysis (if high quality data sets exist)



1) Implications: Climate Change & Coastal protection & Vertical Datum Unification & Navigation

2) Done: various methodologies tested (ocean & geodetic approach) for low resolution surface, here time variable approach

3) What is still needed : high resolution surface in space and time

improved input data (altimetry for coast, currents, winds for validation and integration

improved methods for identifying eddies (fast, automated, e.g. machine learning)

Conclusions (Bullets)

- **Relative & absolute sea level:** Satellite observation are an unique tool for estimating absolute sea level far from the coast and at coasts when tide gauge are missing or incomplete. Together with GPS give sea level change relative to coast, together with tide gauge give Vertical Land Motion. Needed: improved and continuous data processing, no coastal gap

- **Regional Sea level budget:** Altimetry and gravimetry essential for identifying ATL mass balance, allowing separation of steric and mass components, steric effects at distance (ATL). Assimilation of satellite observations in ocean model simulation/reanalysis and land hydrology to be fostered. Needed: improved and continuous data. Hydrological, oceanic and solid Earth changes need to be studied together contribution and limitation of remote sensing.

- **Dynamic Topography:** high resolution dynamic topography needs high resolution input data. Multi-mission altimetry + wide-swatch altimetry needed to detect high features in open ocean and at the coast (e.g. gyres). Additional input : ocean currents by SAR image are extremely important but not yet widely available, quality need to be improved

Recommendation
(on future investments on the Atlantic region)

- **New data, technologies (from space)** : continuity of altimetric and gravimetric missions.
  - Sea level (GNSS reflectometry, 2D wide-swath SWOT) coastal gap and spatial resolution
  - Sea state (from SAR and CFOSAT etc.)
  - Surface Currents (from SAR, SKIM mission)

- **New data (in-situ)** : Co-located TGs & GPS are needed, easy access, central efforts

- **New data (model)** : improved **meteorological data** (e.g. . COSMO-REA reanalysis)
- State-of-the art **ocean models** (downscaling to coast, e.g. NEMO (regional), UG estuarine and coastal SCHISM model - with fine resolution (unstructured grid models)
- Integrating waves, circulation, atmosphere and HD model (e.g GCOAST system)
- **Improved in-situ / remote sensing data assimilation**

- **New methods** (spatial correlation, pattern identification, machine learning)
- Hydrological, oceanic and solid Earth changes need to be **studied together** to better understand contribution and limitation of remote sensing

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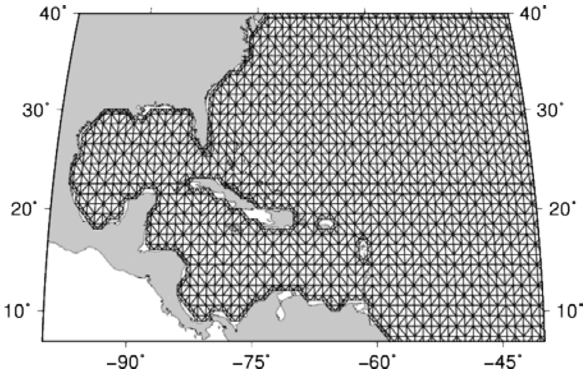
Extra slides

Rietbroek et al. 2016

DT: Proposed Parametric Model: Finite Elements 2/6

Use Finite Elements on a triangulation: cover the ocean, extrapolate to the coast, flexible geometry, approximate the unknown function space



Linear Elements:

- Function values in the nodes
- 3 degrees of freedom
- Composed surface is C^0-smooth

ARGYRIS Element:

- Function values, 1st & 2nd derivatives in the nodes
- Normal derivatives in mid-points of edges
- 21 degrees of freedom
- Composed surface C^1-smooth

The surface is continuously defined in the region of interest

A full covariance matrix can be provided

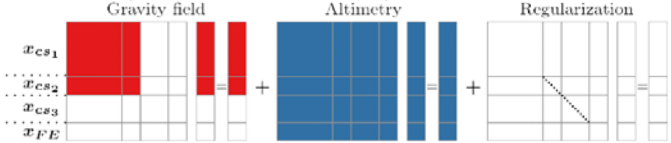
Different observation types/functionals can be easily integrated (e.g. surface currents)

Finite element space determines smoothness conditions (C^0 or C^1)

Example: iterative refinement of along track error model e.g by covariance functions or stochastic processes along the track for altimetric SSH observations

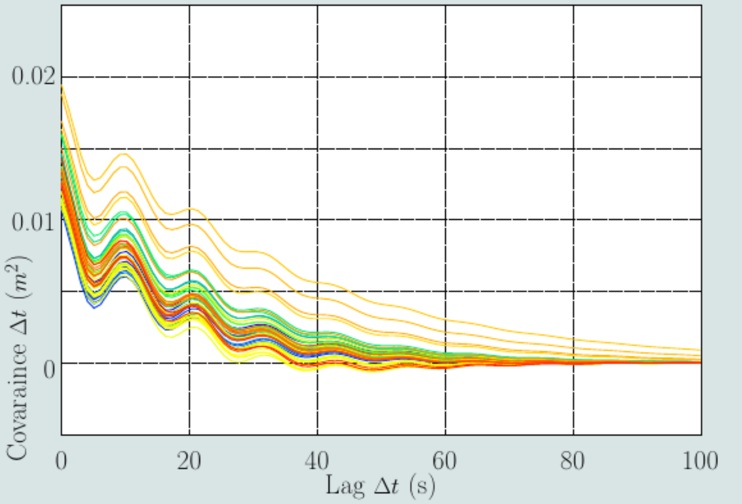
Setup of an iterative procedure:

1. Input data and information
   - predefined finite element setup (triangulation and base function type)
   - predefined spherical harmonic setup (maximal resolution)
   - NEQs of gravity field model: $\mathbf{N}_{gf}$, $\mathbf{n}_{gf}$,
   - OEQs of ssh observation of a mission i: $\mathbf{A}_{ssh_i}$, $\boldsymbol{\ell}_{ssh_i}$, and initial covariance model $\mathbf{Q}^{(0)}_{ssh_i}$
   - initial weights for all observation groups (w_i and w_{gf})
2. Compute NEQs for ssh observations, $\mathbf{N}_{ssh_i} = \mathbf{A}^T_{ssh_i}\mathbf{Q}^{(0)\,-1}_{ssh_i}\mathbf{A}_{ssh_i}$, $\mathbf{n}_{ssh_i} = \mathbf{A}^T_{ssh_i}\mathbf{Q}^{(0)\,-1}_{ssh_i}\mathbf{A}_{ssh_i}$,
3. Combine NEQs (different parameter spaces!)



$$\mathbf{N} = w_{gf}\mathbf{N}_{gf} + \sum_i w_i \mathbf{N}_{ssh_i}, \qquad \mathbf{n} = w_{gf}\mathbf{n}_{gf} + \sum_i w_i \mathbf{n}_{ssh_i} \qquad (1)$$

4. Rigorous parameter estimation (huge dimensional) $\tilde{\mathbf{x}} = \mathbf{N}^{-1}\mathbf{n}$
5. Estimate weights for all observation groups (w_i and w_{gf}), continue with 3.
6. Compute SSH residuals $\mathbf{v}_{ssh_i} = \mathbf{A}_{ssh_i}\tilde{\mathbf{x}} - \boldsymbol{\ell}_{ssh_i}$
7. Analyse $\mathbf{v}_{ssh_i}$ and adjust a stochastic model to $\mathbf{v}_{ssh_i}$, update $\mathbf{Q}^{(1)}_{ssh_i}$ and continue with 2.



=> more realistic error model => better combination of different data sets